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THE EVOLUTION OF THE EARTH[1]

II. Earth-Growth

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In the view that was dominant during the last century—perhaps dominant still—the earth, when it had emerged from its natal conditions and had become a mature planet, was pictured as a molten globe surrounded by an atmosphere embracing all such earth-substance as would be volatile at the temperature of white-hot lava. The earth must then have been a perfect sphere, except as rotation imposed a symmetrical deformation upon it, and even the details of its surface configuration scarcely departed from the contours of a perfect spheroid. Its internal structure must have been symmetrical, the denser material at the center, the less dense in concentric layers about this, the least dense at the surface. Each layer should have been essentially homogeneous in itself. The stresses within the earth, at first, must have been purely hydrostatic, increasing necessarily from the surface to the center.

The evolution of the earth under this concept was actuated by changes of energy within the hot young planet itself, chiefly loss of energy by radiation. At an early stage of this loss, a crust formed over the uniform surface of the symmetrical spheroid, dividing the fluids below from the fluids above. On this crust, the vapors descended, and a universal ocean followed; and then—if we pursue the picture so impressively painted by the old masters in geology—there was a prolonged battle between fire and water, the ocean penetrating to the hot material beneath it and arousing explosive action of a spectacular sort. Lateral thrusts arose from the shrinkage of the cooling globe, followed by bowings, foldings and fractures. Here and there, the crust emerged from the universal ocean and the great contest between the sea and the land was initiated. Thus the postulated evolution was made to arise in simplicity and to go forward in a symmetrical, logical way. It was pictured with great impressiveness—not infrequently with a touch of eloquence, often with a touch of poetry—by the masters of geology in the middle of the last century.

We owe these old masters a tribute of gratitude for the clear views

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[1] Third series of lectures on the William Ellery Hale foundation, National Academy of Sciences, delivered at the meeting of the Academy at Washington, on April 19–21, 1915.

they set forth, and for the logical fidelity with which they followed the premises they adopted, a fidelity largely lost in these later years, by the adherents of the same cosmogonic tenets. This lapse is not without reason, for the later students of the earth have been compelled to accommodate their views to new disclosures of stubborn realities that do not fall into obvious accord with the cosmogonic antecedents so sharply postulated in the earlier years. It is perhaps not far from the truth to say that, in recent years, few geologists have tried to follow rigorously the cosmogonic tenets handed down to them. Usually they have contented themselves with shaping their views to fit the more specific aspects of the phenomena they have had immediately under consideration. A multitude of divergencies from the simple tenets of our forefathers have thus arisen and have come to penetrate modern geologic literature in a most intricate way. The stubbornness of the realities revealed by progressive inquiry has amply justified a swerving from inherited tenets. It has equally invited a loosening of the hold of doctrines that depend on these tenets. In recent years the insubordination of new determinations to old interpretations has risen to declared refractoriness. The old problem of the origin of the continental embossments and the abysmal basins, the problem that lies at the very threshold of earth science—always a troublesome problem, because of the great range of the inequalities—has lately assumed a new form and become a burning question of the hour. Under the stress of time-limits, let us take this as a type of a large class of new issues. I refer to the fundamental question that lies beneath the growing doctrine of isostasy, the origin of the differentiation of specific gravities deep in the crust of the earth necessary to actuate isostatic movement, the very basis of isostasy. In this lies a grave challenge of the molten concept of the primitive earth. Very cogent reasons have been adduced from geodetic data, particularly by Hayford and Bowen, for the belief that the protrusions of the continents are in isostatic balance with the depressed segments beneath the oceans. It is hence inferred that the material beneath the continents is as much lighter than that beneath the oceans, as the former are protrusive and the latter depressive; in other words, the difference in the specific gravity of the rock columns beneath the continents and beneath the oceans, respectively, must extend far enough down to compensate for their differences of height. A great mass of refined observations support the isostatic view, at least in its major features.

But from the earliest days of geologic record, the atmosphere and the hydrosphere have been persistently cutting away material from the continents and depositing it in the basins, while the continents have been pushed up, at repeated intervals, and the denudation renewed, else the sea would long since have crept over the whole land. Many thousands of feet have been cut away from the oldest known lands. Now this implies that the low specific gravity beneath the continents has been deep enough and great enough to actuate isostatic movement, again and again, as the unloading of the land and the loading of the great water-basins has required. Differences of specific gravity adequate to this must have had a competent source; the differentiation must have been deep enough and great enough to have retained its efficiency through all the ages in spite of the persistent efforts of denudation and transportation to effect an equilibrium, not only, but it must have been great enough to leave the present undetermined resources available for future isostatic movements.

Now in a molten earth there should have been, at the start, a perfect isostatic balance, in the fullest sense of the term. An adequate cause for any non-isostatic differentiation in such a liquid mass seems wholly unassignable; certainly it has not been assigned; on the contrary, there are the most obvious reasons why the state of gravitative balance should have been initially perfect under the molten theory and should be preserved, for the dominant tendency of surficial action is perpetually toward equilibrium. The agencies within, like the agencies without, should have worked hand in hand to maintain the isostatic stability inherited from the original state. The present state does not, therefore, seem to flow logically from the assigned initial state.

But the case does not rest alone on logic, however cogent. If, in some unexplained way, there arose a deep differentiation of specific gravity of one type beneath the continents and of the opposite type beneath the oceans, and if the continents were thus forced to rise as their surfaces were cut away, the original embossments would, by this late day, have been cut down many thousands of feet, and we should now have free access to this much of the original molten interior of the earth. Our geologic forefathers, with their logical fidelity, so interpreted the deeper terranes so exposed in the heart of the old embossments, and some of us were indoctrinated with this concept in our youth. But as soon as petrologic science had come into possession of its modern efficient tools, it was discovered, almost simultaneously in the several critical regions then under competent investigation, *that the oldest known rocks are surface rocks and that the supposed original igneous rocks of the sub-crust are merely local intrusions.*

Taken together, these determinations constitute a formidable obstacle to the further acceptance of the inherited view. There is an absence of such observational testimony in support of the hypothesis of a once molten interior as we have a right to expect, such indeed as our geologic forbears did expect, not only, but supposed they had found. There is now added to this deficiency the adverse implications of such a deep differentiation of specific gravity as to force deformative readjustments, even at this late day, in spite of all previous partial adjustments.

This seems quite incompatible with a primitive molten state of the earth. To some of us its adverse import is wholly decisive. If there is a line of escape, consistent with logical fidelity to observed facts and physical principles, I must leave it to others to find it.

But we are less concerned with doctrines that fail than with doctrines that seem to hold out working promise of a true interpretation. The renewed protrusion of the continents and the continued receptivity of the oceanic basins, constitute the working prerequisites of geology, the very *sine qua non* of our science. The verity of their initiation and their maintenance throughout all recorded geologic history must be justified by any system of doctrine that has any claims to serious consideration. We feel, therefore, the call to dwell, in proportion to their importance, upon these fundamentals, in respect to which faith has been so much disturbed by recent disclosures.

The cosmogonic postulates set forth in the last lecture gave a specific working basis for an alternative picture of the early states and of the basal constitution of the earth. Briefly, these were a nebulous knot, as a center of growth, and much scattered nebulous matter as food for growth. The central portion of the knot was probably in a dominantly inter-collisional state, while the outer portion was almost inevitably in a dominantly orbital state, the latter circling about the former and limited outwardly by the sphere of control of the knot. The intercollisional portion should have rapidly collapsed into a dense spheroid so far as composed of rock-substance. The portion that revolved about this, after the manner of minute satellites, *i. e.*, satellitesimals, was collected only as the occasional collision of one satellitesimal with another drove them from their orbits into the earth nucleus or into the moon nucleus, or else they were driven in by infalling bodies from without, *i. e.*, planetesimals. The aggregation of the knot was not then a simple matter of gaseous collapse by cooling. What portion of the knot belonged to the intercollisional and to the orbital categories, respectively, is at present indeterminate, but progressive study tends to increase the probabilities that favor the orbital state and to diminish those that favor the intercollisional state. The nucleus of the knot that condensed in gaseous fashion to form the primitive core of the earth may have been no more than a minor fraction of the adult earth.

The scattered matter of the nebula, outside the knot, could apparently have been in no other than a state of movement about the sun. The scattered integers, whether moleclues or small aggregates, must apparently have pursued orbital paths of planetary type about the sun, that is, they must have been minute planets, or planetesimals. These were liable to fall into the earth knot in the course of their revolutions about the sun. The process must have been slow, as was also the ingathering of the satellitesimals of the knot, but each aided the other.

INTERNAL REORGANIZATION

An important deduction from such a genesis is the extreme heterogeneity it must have given the substance of the earth and the internal reorganization that such heterogeneity must have induced. There should have been, to be sure, some selective action, because the more inelastic material would concentrate faster than the more elastic matter, and the magnetic material would doubtless be gathered into the core, if it were magnetic, as is probable, faster than the non-magnetic material, but nevertheless much heterogeneity must have prevailed.

The atmosphere should also have served a distributive, as well as a slightly selective, function. As the planetesimals plunged into the outer atmosphere of the juvenile earth, they must have been largely dissipated into dust, if we may judge from the effect suffered by meteorites. These are largely consumed in the very thin upper air; only a very small fraction reach the earth's surface, and these are perhaps more massive than were the planetesimals. The planetesimal dust so generated no doubt floated long before it found final resting place on the earth's surface. Whatever heat was generated in the plunge into the atmosphere must have been largely radiated away from the upper regions, and the temperature of the accretional portion of the early earth could scarcely have been high.

The distribution of the accessions to the earth was thus incidentally conditioned by the atmospheric circulation. Descending currents naturally took precedence in bringing the dust down, but their dryness and turbulence near the earth's surface tended to hold the lighter material longer in suspension than the heavier; the action was hence slightly selective. Precipitation, largely associated with the rising currents, brought down all classes of dust within its reach. The first lodgment was further modified by the waters of the juvenile earth with some further selective action. On the other hand, the internal agencies that shaped the earth-body, potentially shaped also the work of the waters, for these followed the slopes of the land and gathered in the basins of the growing surface. Both the irregularities of the surface and the water, in turn, modified the circulation of the atmosphere that swept over them. And so the shaping of the earth-body by planetesimal growth was the composite product of the three great geologic factors, the atmosphere, the hydrosphere and the lithosphere, and should have been appreciably differentiated in specific gravity.

THE INTERNAL STRUCTURE OF THE EARTH

The material of the accessions should have taken on a more or less stratiform arrangement under the action of the atmosphere and hydrosphere. Such molten matter as was poured forth from within likewise should have assumed a rude stratiform arrangement. The combined effect of these processes was to give the earth a concentric structure, built up of very heterogeneous matter.

At the same time there were processes that tended to develop a radial structure traversing these stratiform layers much as the medullary plates of a tree trunk traverse its concentric layers of growth. Such lavas as rose from the depths doubtless either insinuated their way through seams, crevices, schist planes, and other lines of weakness, or fluxed pathways for themselves along ducts of their own making. In addition to these, the compressions that arose from growth, from transfers of molten matter from the depths to the surface, from changes of temperature, from molecular rearrangements under pressure, to secure greater density, all contributed to readjustments, recombinations and recrystallizations accommodated to the stress-differences whose least axis usually pointed in the direction of the surface. Lateral compression is a familiar phenomenon, vertical schistosity is its normal result. Diastrophic agencies came into action at a very early stage, and hence at a low horizon within the earth and their effects upon the structure of the earth were extended upward to the successive layers that were added at the surface. The earth is thus supposed to have acquired a vertical schistosity which had its initiation at great depths.

PARTIAL LIQUEFACTION AND THE PRESERVATION OF SOLIDITY

The system of internal liquefaction and extrusion, assigned under the accretional hypothesis, departs rather radically from inherited views based on a supposed molten globe. It therefore invites critical consideration. Neglecting the very heart of the earth that is supposed to have grown from the gaseous nucleus of the knot of the nebula—the conditions of which are least certain and whose proper treatment is inhibited by time—let it be noted that the matter gathered to the earth-nucleus as aggregates, or as accretional dust, was highly heterogeneous. Assuming that it was cold when deposited, heat arose from compression as layer was added to layer. Such radioactive matter as the accessions contained also generated heat at multitudes of minute points. The increasing pressure, so far as uniform on all axes, antagonized liquefaction. With such a slowly rising temperature, so distributed and so antagonized, it may be assumed safely that liquefaction would start, so far as it started at all, with those points where particles mutually most soluble or most fusible were in contact with one another, or where most heat was generated by radioactive action, or where the two cooperated. If the mobile matter so generated slowly were removed about as fast as it gained workable volume, the main surrounding mass would remain solid. We have just named a list of stresses that may well be held competent to force at least all the lighter liquids toward the surface. We shall presently discuss these further.

It is now known from concurrent evidence—the most conclusive of which springs from the recent work of Michelson, Gale and Moulton on the body tides—that the earth is highly rigid and elastic. Aside from cosmogonic considerations, the grounds of which we have already challenged, we know of no reasons for assigning the earth any other than the rigid state, at any time during the geologic ages. The planetesimal hypothesis assumes that the elastic rigid condition prevailed, at least in the outer half of the earth, throughout the history of its growth. It holds that the accessions were added in the solid state, and that such liquefaction as later arose in this solid matter must always have been merely partial and selective, and that the liquefied material was forced, by prevailing stresses, to the surface as fast as it reached working volume. This is a radical departure from the inherited concept of a molten interior. The stresses that are believed to affect the interior of the earth are serious obstacles to the supposed existence of great reservoirs of liquid matter, lying quiescent for long ages, and undergoing magmatic differentiation under assumed static conditions. The great distortions that have certainly affected the earth to the greatest accessible depths and that are most intense in the deeper rocks, seem to be specific evidence at variance with the assumption of such protracted quiescent conditions. The newer view postulates effective stress conditions permeating the globe at all times during its adolescent, as well as adult, history, and that these effective stresses tended to force to the surface all mobile materials, except possibly some whose specific gravities were sufficiently high to resist the ascensive pressure.

The new view makes its first and most fundamental appeal to the differential stresses imposed by changes of rotation. The primary stresses of rotation give evidence of having been the greatest that have been imposed upon the body of the earth, except those of gravitation, which are hydrostatic. According to Sir George Darwin, the rotational stress-differences are eight times as great at the center as at the surface. The potential stress-difference that would become actual at the center of the earth by the arrest of the existing rotation amounts to 33 tons per square inch. The tidal stress-differences have a similar distribution, but they are relatively feeble, though persistent and pulsatory. The more general class of stresses that arise from loading and unloading through erosion and transportation perhaps have a somewhat similar distribution. The static stresses due directly to gravity, range from one atmosphere at the surface to about three million at the center. From these cooperating stresses, a persistent urgency to escape to the surface is believed to have been brought perpetually to bear on the mobile and, in the main, lighter liquid material as fast as it was generated. The less soluble, more refractory, and, in general, denser material remained behind, but probably approached mobile conditions sufficiently to permit rather free molecular rearrangements, especially such as would give higher density. Under the general principles of endothermic action, heat-absorbing combinations may be assumed to have taken place with corresponding limitations of liquefaction. Crystalline rearrangement in the interest of density, and at the same time consistent with high elastic rigidity, is thought to have been favored and to have taken such forms and mutual relations as to give schistosity favorable to deformative movements.

Such liquefaction as took place would consume heat, in addition to that of the endothermic recrystallization, while the escape of the liquid material to the surface carried out this latent heat, as well as a due portion of sensible heat. Incidentally, the escaping lavas carried out also radioactive substances and gradually reduced the heating process. The compressibility also declined with the progress of compression, and this source of heat also declined. With compression and with the increase of static pressure, the rigidity should have increased. So the complex process inherently tended to an end of its own making.

The process of vulcanism is thus made a means of removing to the surface the excess of internal temperature, as it arises, together with the source of that temperature, performing in this way a service closely analogous to the process of perspiration in the animal body. This view is eminently consistent with the tidal and the other astronomic indications of the elastic rigidity of the earth that have recently become so declared, and also with seismic data whose evidence is less complete, though strongly tending in the same direction. It is also in harmony with the conclusion, reached by special students of the subject, that radioactive substances are chiefly concentrated at the surface. Still further, it is in harmony with the acidic composition and the low specific gravity of the outer part of the earth. The view seems also to be in fair consonance with what is known of the eutectic nature of rocks, the selective production of magmas, and the progressive differentiation of magmas, both in their ascensive and in their descensive careers.

Such effusive matter as reached the surface in the earlier stages was buried later by the infalling planetesimals and planetesimal dust, and so it was again subjected to selective processes, with further differentiation, and this might be repeated again and again, so that, in the end, there was a progressive concentration of the more refractory and the denser material toward the central parts, and of the lighter and more solvent, toward the outer parts. This selective action was of course superposed upon the selective ingathering of planetesimals, dependent upon magnetic and inelastic properties, and upon the selective action of the atmosphere and the hydrosphere. Thus, under this concept, the earth came to its maturity slowly under selective agencies that tended at all stages to differentiate its material.

So also, under this concept, deformative agencies came into action early and persisted through all stages of growth, though at all times more or less periodic in their specific manner of action. These deformative agencies now claim our attention.

ORIGIN OF THE GREAT PHYSIOGRAPHIC FEATURES

The most notable of past attempts to account for the continental embossments and the oceanic basins, in accordance with the theory of a molten earth, was undoubtedly that of Lothian Green, who appealed for his first premise to the fact that a spherical surface embraces the maximum of matter within the minimum of surface, and that this should have obtained in the primitive state of the earth. For his second premise, he urged that the globe, when forced to shrink from cooling, would tend in the direction of that symmetrical form which had the minimum of content with the maximum of surface, the tetrahedron. The cogency of this logic I must leave to your own judgment. On this concept, arose the doctrine of the tetrahedral earth. Assuming that the duodecahedral form of the tetrahedral type was early attained, Lothian Green located the continental protuberances at certain of the angles and the oceanic basins at alternate angles. The logic was frankly based on the doctrine of a molten earth and does not seem to be transferable to an accretional earth.

Under the planetesimal view, it seems scarcely less than necessary to assume that the great differentiations of the earth's surface arose from specific deformative stresses that came into action early in the process of growth and were more or less recurrent throughout the whole adolescent history of the earth. The controlling influence that gave shape to the juvenile earth seems to have arisen from changes of rotation. Rotation is far and away the greatest of all the deformative agencies to which the earth has been subjected. Its residual effect—not its total effect—is now seen in a radial difference of thirteen miles between the polar and the equatorial radii, but this is only the net result of a long series of earlier effects of opposite phases. The rotational stresses permeate the entire mass of the earth and, as already remarked, are greater at the center than at the surface. Such pervasive and penetrating stresses are preeminently suited to produce broad, deep, and pervasive deformative effects. The breadth and symmetry of the direct rotational effects are seen in the great graduated equatorial bulge and in the broad graduated polar depressions. This symmetrical distortion of the sphere satisfies the *primary* demands of rotation *but not the incidental demands of changes of rotation.*

The bulging and the depression of these broad tracts involved tension and compression in the segments so affected, and lines of accommodation to these stresses were requisite. It is assumed that these lines of accommodation would define as few broad divisions of appropriate form and magnitude as would serve to satisfy their main requirements, leaving minor requirements to be satisfied by minor accommodations. It is assumed further that these major divisions would be so related to one another as to act reciprocally, one set rising in the equatorial regions, the other set sinking in the polar regions, and the reverse, according as the rotation was accelerated or was retarded. Since the earth is held to have been a rigid body, it is held—and this will bear emphasis—that the units of action would be as few as could fairly satisfy the main demands of the case, and that these parts would be as simple and symmetrical in their forms and in their working relations to one another as practicable.

The probabilities of successive oscillations between acceleration and retardation of rotation are dependent on the specific history of the formation of the globe. Under the planetesimal hypothesis, a part of the earth's rotation was inherited from the knot that formed its center of growth, but an important portion also arose from the momentum of infalling planetesimals. In the nature of the case, some of the infalls tended to accelerate rotation, while others tended to retard it, and so changes in the ratios of these two classes, arising from irregularities in the distribution of the planetesimals, tended to change the rate of rotation. Time does not permit me to give reasons for the conclusion that there was an *equilibrium rate of rotation* about which oscillation should have been an inherent tendency.[2]

Now with every increase of acceleration there was depression and crowding at the poles, while there was bulging and tension at the equator, and between these rising and falling areas there was a neutral or fulcrum zone which neither rose nor fell, but under which a shift of matter took place from the depressed to the lifted side. With every retardation of rotation, there was the opposite effect. No portion of the earth was free from these influences. Just how the earth accommodated itself to these profound stresses is our problem. So far at least as the tensional alternative is concerned, there are many phenomena in nature that teach us how the easement is accomplished, and where the yield tracts lie. There are some which show us less simply and less unequivocally how relief from compression is effected. The most instructive example is found in the cooling of lava into basaltic columns. From a study of these, it is seen that the required accommodation is effected by three parting planes diverging from the points of greatest tensional stress, at angles of about 120°. There is, of course, much variation from this precise angle when the material is even moderately heterogeneous, for the action is but a mechanical accommodation of the stresses, and has none of the precision observed in the formation of crystals.

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[2] These are given in "The Origin of the Earth," now in the hands of The University of Chicago Press.

On the basis of this principle of action, it is assumed that a threefold partition would obtain at each of the poles when under tensional stress, and that the yield tracts would extend to the fulcrum zones. The position of the two fulcrum zones would shift with the degree of oblateness, but they may be conveniently spoken of as lying not far from 30° latitude north and south. The segment so defined surficially would form only one half of the reciprocating unit. This, as seen on the surface, would have the form of a spherical triangle. The other half-unit that must cooperate with this one in reciprocal action, could be formed in the simplest and easiest way by similar yield lines crossing the equatorial belt and converging to a point in the fulcrum zone of the opposite hemisphere. The reciprocating pairs would thus consist of similar triangles—at the surface—back to back, the one wholly in the rising area, the other wholly in the sinking area. Three such reciprocating pairs would then surround each pole. If one set took precedence, as would be natural, the other would be forced to alternate with it. The two sets would thus interlock across the equatorial belt. Each working pair of triangles would form a quadrilateral at the surface, and would extend to the center, where the six apexes would come together. The earth would thus be divided into six pyramidal sectors, symmetrically related to the axis of rotation, symmetrically related also to the stresses to which they must yield, and embodying a very simple mode of meeting the requisite changes of form. This concept of a hexafid earth has some resemblance in form to the factors of the tetrahedral earth of Green, but it starts from entirely different premises and is based on radically different considerations. The hexafid division is in no sense a crystalline process, but merely a mechanical adaptation to variations of stress imposed by the pervasive effects of changes of rotation.

But no very close approach to perfect hexafid partition could probably arise from stresses working on the complex texture of an accretional earth. Besides, certain definite tendencies to inequality of development appear to have arisen as the segmentation went on. There was the law of progressive dominance. Whenever in the course of growth, any division came to preponderate in mass or density, this very preponderance gave advantage in the acquisitions that followed. Dominance not only tended to its own perpetuation but to the increase of its own preponderance. It naturally resulted that some of the sectors grew more than the others. The basins of the southern hemisphere seem to have taken precedence of those of the northern, and the basins of the Pacific took precedence over those antipodal to them. These two preponderances united to give a preponderant water hemisphere, with its center near New Zealand, and a preponderant land hemisphere, with its center in southwestern Europe.

There was also the law of alternation. When any pyramidal sector sank from superior weight, it crowded aside the adjacent sectors, and the belts of easement between them were squeezed in proportion as adjacent basins sank. And so depressions and elevations alternate around the globe.

There was also the law of opposites. Whenever any pyramidal sector sank by reason of superior weight, it favored reciprocal rise on the opposite side. So, as a matter of fact, depressions stand opposite to embossments about the globe.

There was also probably an adjustment of the sectors relative to one another. Ideally, the sectors might stand point to point, but this is an unstable adjustment, and amid the inequalities and distortions that arose, the sectors would naturally be shifted in the direction of least resistance, so that the sinking heavy sector, on one side, would come to stand opposed to a yield tract on the antipodal side. And so basins should have come to be antipodal to protrusions, if not already so at the outset. In harmony with this, it may be observed that the North American embossment stands opposite the basin of the Indian Ocean, the Australasian embossment opposite the basin of the North Atlantic, the great east central basin of the Pacific opposite the great protuberance of Africa, the South Pacific opposite Asia in part, the Antarctic continent opposite the Arctic basin, while the great oceanic sag around the Antarctic continent stands over against the great land belt in the high latitudes of the northern hemisphere.

There are a multitude of interesting details and qualifications, and some incongruities, upon which it would be delightful to dwell were there time. In the very tentative and imperfect presentation of this doctrine which alone is possible here, let us content ourselves with the merest glance at certain salient illustrations of the suggested segmentation of the earth.

Starting with the hemisphere of heaviest segments and largest present increments—which therefore probably took precedence in action—the three oft-noticed poleward-pointing extremities of Africa, Australia and South America illustrate the three-fold division of the polar region, in fair harmony with the terms of our interpretation. Following the South American axis northward to the vicinity of the fulcrum zone, the ideal scheme demands bifurcation and angulation. In harmony with this, marked structural features diverge to the northwest and northeast. The former strikes through the Isthmus of Panama, the states of Central America—with the Antilles as a duplicate line—and onward to the vicinity of the fulcrum zone of the northern hemisphere, where the dominant structural lines should turn in a second angulation, toward the north pole. This is partially realized, but is much obscured by superimposed features that cannot here be discussed.

Turning back to the point of bifurcation in South America, "the Backbone of Brazil" strikes northeasterly, and, save for the interruption of the constricted connection between the two Atlantics, is continued in the structural lines of northwestern Africa to the critical zone of angulation on the borders of Africa and Europe.

Turning back again to the south African axis, it is to be noted that, near the proper latitude for bifurcation, two ancient crystalline terranes diverge in lines nearly parallel to the borders of the continent, and extend across the equatorial belt to about the assigned zone of angulation in the northern hemisphere, where converging deflections toward the north pole are encountered, notably the west border of Europe and the Ural mountains.

Both Australia and New Zealand have southern prolongations that seem to represent, in a duplicate way, the third meridional easement tract of the south polar regions. At about the assigned latitude, a broad strand of northwesterly trending structural lines run through the East Indies and connect Australasia with southeast Asia. The trend of this remarkable strand is continued to the latitude of the northern zone of angulation where a complex series of divergencies is encountered with a northerly and northeasterly trend.

In perfect symmetry and completeness obtained, there should be three main yield tracts from the poles to the fulcrum zones not far from 30° Lat. N. and S., while between these there should be oblique trends. At the same time, the great continental embossments and the great abysmal basins of the two hemispheres should stand in alternate or offset positions relative to one another. These basal requirements of the interpretation should be rather distinctly discernible, though much obscured by outgrowths and distortions. The North Atlantic should be offset to the west relative to the South Atlantic, North America relative to South America, the North Pacific relative to the South Pacific, Asia relative to Australasia. These radical requirements are strikingly realized. North Africa and Europe are less strikingly offset relative to South Africa, but the tendency is marked. The obliquity of the trends in the equatorial belt is strikingly displayed in the East Indies, and in the West Indies and isthmian connections between the Americas. It is betrayed also in the trends of the singular physiographic features that affect the junction area of Africa, Asia and Europe.

Time will not permit us to lapse into explanatory details. The scheme of interpretation only calls for the detection of a deeply buried embryonic framework on which other agencies have built the adult configurations of the globe, and on which they have imposed their own characteristics.

DYNAMIC ORGANIZATION OF THE ATMOSPHERE

The working relations of the primary segmentation of the earth-body to the dynamic organization of the atmosphere, were close, both in causation and in effect. There were striking analogies between them. The broadest features of the atmospheric circulation are now, and probably were in the earth's juvenile stage, as simple as the broad features of rotational deformation. So too, the secondary adjustments of the atmospheric circulation in the two hemispheres are now, and probably were from the outset, very similar to the secondary adjustments of the earth-body. All the significant features of this analogy can not even be mentioned. We can simply note that, over the great oceanic basins in the latitudes of the fulcrum zones, there are oval systems of circulation centering about the areas of high atmospheric pressure, which match, in a general way, the centers of high specific gravity in the basin sectors below. On the borders of these ovals, there are tracts of conflict and of high precipitation, corresponding to the disrupted adjustment tracts of the earth-body below. These gyratory systems and these tracts of precipitation influenced fundamentally the deposit of planetesimal dust, and thus gave direction to the growth of the earth, while, at the same time, they themselves were profoundly influenced by the configuration of the earth-body, and by the waters gathered into its great basins. And so the three great factors, atmospheres, hydrosphere, and lithosphere, cooperated in building up and giving shape to the great features of the earth.

It is obvious that whatever planetesimal material found lodgment on the lands was subjected to greater leaching than the portions that fell into the waters. It appears that the average specific gravity of the elements leached away must have been slightly higher than that of the portions left behind—in the form they would finally take after burial and metamorphism—so that the protuberances came to be formed of slightly lighter material than the basins, and hence, in deformative actions, the basins took precedence in sinking and the continents were accommodated to this. This contributed to the permanency of the great features of the earth which, in turn, influenced the atmospheric circulation.

We find then, in this mechanism, reasons for the observed lower specific gravity of the continents and the higher specific gravity of the sub-oceanic material. In this, also, lie reasons for the continuous maintenance of the continents, and hence the perpetuation of continental life, as well as the reciprocal maintenance of shallow-water oceanic life. Some of the greatest generalizations of geology thus find inherent support and adequate elucidation in the very origin and constitution of the continents and of the ocean basins, while in this inherited constitution are found cogent reasons why these great features are, and should ever remain, protrusive and depressive, respectively.

We are thus brought to conditions that are fundamental to the evolution of life on the earth. This fascinating theme I must leave to my successor. It is to be noted, however, that the physical evolution of the earth predetermined, in large measure, the lines along which the life evolution of the globe was compelled to proceed.

When the great embossments and the deep basins had become determinate, and when the earth's growth had been completed, there followed a long history of denudation of the land, of filling of land-girt basins, and of building of terraces about the borders of the lands. There were base-levelings and great transgressions of the seas, covering sometimes half the continents, but never, in the known history of the earth, wholly submerging them. Before complete submergence was reached, rejuvenation intervened; the continents were re-elevated and the seas withdrawn by further sinking of their basins, and a new period of life evolution ensued. The whole sea-history seems to have been a succession of encroachments followed by retreats, with correspondent expansions and restrictions of sea life, while the land areas were reciprocally reduced and expanded with corresponding restrictive and expansive evolutions of land life. Thus the familiar evolutions of the well-known history of the globe went forward controlled, in a profound way, by the hidden powers of renewal inbred in the early organization of the earth-body. The whole evolution was, at the same time, profoundly influenced by the constitution of the atmosphere and by climatic conditions.

THE EVOLUTION OF THE ATMOSPHERE

The evolution of the atmosphere under the older cosmogonic views took the form of a great decline from a vast primitive envelope through a long series of depletions, to the relatively emaciated conditions that obtain to-day, under this interpretation. All this is too familiar to need more than simple reference. The alternate view here entertained pictures the atmosphere as growing up from small beginnings and maintaining itself throughout the ages by alternate enrichment and depletion from within and without. A bare sketch of some of the least familiar of these tenets is all that can be given.

The lower atmosphere is eminently collisional, each molecule colliding with other molecules with prodigious rapidity. This condition prevails upwards until the tenuity of the air becomes so great that molecules, bounding upward from encounters, find no other molecules in their path until gravity has had time to arrest them and draw them back toward the earth center. There are thus substituted vaulting leaps for to-and-fro motions. A fountain-like zone supervenes upon the the collisional atmosphere. This krenal atmosphere is necessarily very attenuated, but the vaulting molecules do not entirely escape collision with one another. From these mid-vault collisions rebounds, more or less tangential to the earth, arise in a certain proportion of cases. Under the law of probabilities, a certain percentage of molecules thus rebounding have sufficient velocities to take orbital courses about the earth. When they have once entered upon these orbital courses, molecules may remain indefinitely in them, if not driven from them by some intervening agency. This introduces a distinctly new factor, for this permits accumulation to go on until this very accumulation checks itself. The logical series consists, therefore, in a vaulting ultra-atmosphere, springing necessarily from the summit of the collisional atmosphere, and, in turn, giving rise to an orbital atmosphere which must tend to accumulate until an equilibrium is reached, in which the orbital atmosphere gives back, or throws outward, as many molecules, in the long run, as it receives.

Now a limit to the outward extent of the vaulting molecules and of the orbital molecules is found in the limits of the sphere of the earth's control. The minimum radius of this, according to Moulton, is a million kilometers (620,000 miles), the maximum radius, a million and a half kilometers (930,000 miles). Under kinetic laws there seems no logical escape from the conclusion that a certain proportion of molecules vault to the limit of this sphere of control and beyond it, and that orbital molecules occupy, in their extremely attenuated way, the whole of this sphere also. Those molecules that pass beyond this sphere enter the sphere of the control of the sun and are lost to the atmosphere of the earth.

Similar logic applies to the ultra-atmospheres of the sun whose sphere of control envelopes the earth. The sphere of control of the earth has been sweeping through the sphere of control of the sun throughout the entire history of the earth. As a result of these relations, it is logically inferred that there has been a feeding in of molecules from the sun's ultra-atmosphere, during the whole evolution of the earth, and that these exchanges have tended toward an equilibrium by which the scanter atmosphere, whichever it may happen to be at any stage, has been fattened by the richer atmosphere. Logically this relation obtains to-day.

If this interchange were solely dependent on mechanical action between the molecules, its quantitative sufficiency might possibly be open to question, but this interchange is the basis for cooperative action by electric and magnetic agencies. The competency of these, while as yet undetermined, is very probably important. Electric and magnetic actions not only abet the mechanical distribution, but offer possible, if not probable, solutions of the grave problems that arise respecting a constitution of the early atmosphere suitable for the generation and maintenance of terrestrial life. It is a notable fact that the actively combining molecules of the earth's atmosphere belong to a special class which have a general tendency to bear a negative charge of electricity, among which the vitally essential element oxygen is chief.

Functions of Oceanic Circulation

The superficial circulation of the oceans is a result of the winds, but the deep circulation appears to be the product, in part, of the differences in density of the sea water. At present, two great influences seem to be contesting for the mastery of the deep sea circulation, and, through such dominance, for the mastery of our coming climate. The dominant circulation is now controlled by the polar regions, especially by the Antarctic. The density of the sea water is there increased by low temperature and by some concentration of salts through freezing. With this higher specific gravity, the polar waters outweigh the warmer waters of the lower latitudes and descending flow along the ocean bottoms into the depths of the abysmal basins, rising ultimately in the equatorial tracts to depress the temperature there and to force the heated waters poleward. This deep-sea circulation is, without doubt, one of the elements that perpetuate the semi-glacial conditions of our times. Over against this, is the work of evaporation in the arid tracts, notably the 30° belts. By such evaporation, the waters of the Mediterranean are distinctly higher in specific gravity than those of the Atlantic and, as a result, the dense, though warm, saline water flows out through the Straits of Gibraltar into the Atlantic, spreading out in spatular form nearly across the North Atlantic, and descending to great depths. Similar dense waters flow out from the Red Sea, while under the great evaporating belts analogous condensations are taking place, the effects of which are felt to very notable depths. It is not known whether this increase of density in the warm tropical regions is gaining upon the density-effect of the polar regions or not. We must wait for future observations to decide how the battle is going. But it is clear that if the intensities of polar cold were mitigated, as in time they no doubt will be mitigated by the wearing down of the heights of the land and by the encroachments of the sea, there is reason to believe that the density which springs from evaporation in the low latitudes will gain the mastery over the polar water, and will sink to the bottom of the sea, filling the basins with warm water. This heated water creeping to the polar regions would carry warmth where now there is frigidity, a natural water-heating system of a stupendous sort. This seems the most probable explanation of the extraordinary fact that throughout the larger portion of earth history, so far as we are able to decipher it, mild climates, even sub-tropical climates, have prevailed in high latitudes, notwithstanding the adversities of their long winter nights, so notably devoid of heat from without. It seems probable that the conditions which favor the dominance of polar cold, at intervals, and the dominance of tropical warmth, in the longer periods between, is determined by the elevation and the configuration of the land, especially that in the polar regions. The present cold oceanic circulation is known to be dominated by the Antarctic Continent and perhaps sprang initially from the geologically recent elevation of that continent. As it shall be cut away by the wear of the surface and the gnawing of the sea, its dominance will no doubt disappear and the dominance of tropical circulation take its place.

Correlated with these temperature changes of the oceanic waters are atmospheric absorptions and interchanges of gaseous content of a vital nature upon which time forbids us to enter.

Projecting these interpretations of the present oceanic junctions back through the geologic ages, they seem to imply successive alternations of remarkable warmth in high latitudes and glacial cold in relatively low latitudes, and corresponding climatic stress effects on life evolution and life distribution.

This system of interpretation assumes that the atmosphere has been maintained from the beginning of the earth's mature history in a state of approximate equilibrium with the atmosphere of the sun; hence an essential uniformity in volume and in constitution have been preserved unbroken from the dawn of life to the present. At the same time, it is held that, subordinate to this essential uniformity and this equilibrium, there have been notable fluctuations in volume and in constitution, due to variations in feeding from the interior of the earth, variations of depletion by chemical interaction with the rocks, and variations in the degree of absorption into the hydrosphere. The atmosphere has been subject also to variations in the retention of solar heat—the essential factor in climate—due not only to variations in constitution, but to variations in the intensity of vertical circulation promoted by surface features. Out of combinations between this automatic regulation of the fundamental constitution of the atmosphere and the oscillations of terrestrial conditions that arise in succession, spring, we think, the essential features of the evolution of the earth's climate, so far as they are terrestrial at all.

Thus far I have tried to emphasize the more fundamental of the dynamic agencies that seem to me to lie back of the physical evolution of the earth. Until the whole history of the earth, early and late, shall be worked out into an accepted interpretation, the *reasons* for the interpretations we entertain are quite as vital as the interpretations themselves. The breadth of the theme has made imperative a most cruel and partial selection. I think I may assure myself that no one else will fully justify the partiality of the selections I have made. It has seemed to me, however, more vital to dwell upon the genetic and the fundamental, than upon the more declared features of the record. These are better deployed, relatively, in the literature of the earth-sciences, and are accessible in our ampler texts. They are the common ground on which we all unite, with more or less complete unanimity.

In a closing sketch of the accepted eras of the earth's adult history, it will be possible to touch only on a few high points. Our scant selection can be justified only by frankly affirming that there are other high points quite as worthy of emphasis.

GREAT ERAS OF EARTH HISTORY

The lowest accessible record is found in a great complex of crystalline rocks whose metamorphism has somewhat obscured their original state. An essential portion of the complex terrane is the work of its own time; the rest was intruded at later dates. The primitive portion carries clear evidences that it was formed at the surface by sedimentary processes, eolian, aqueous, igneous, or pyroclastic. But this portion has been so much intruded, or traversed, by lavas escaping the pressures of the interior, that this immigrant factor obscures and, in some degree, masks the prior sedimentary element. It is to be noted, however, that all subsequent effusions of lava traversed this basal series, and so added to its complexity, and that it was affected also by all the later deformative actions. None the less, eruptive action seems to have been more prevalent in these Archean ages than in those that followed. In its earliest adult stage, the fires of youth seem yet to have been specially active, and the master events seem to have centered about igneous and metamorphic action—but it would be a serious error to overlook the vital contribution that the atmosphere and the hydrosphere cast into this, the earliest of the accessible lithographic records. There are signs of life, but they reveal little of its nature.

There followed this basement complex, a series of great terranes in which the dominant elements were more declaredly the products of aerial decomposition and of aqueous erosion, assortment, transportation, and deposition, though here the igneous factor cast in a very notable contribution also. There are left few identifiable relics of life, but there is abundant evidence of organic action. Between this Proterozoic group and the underlying Archean, lies a great unconformity, and within the group itself there lie scarcely less great unconformities, all of which imply that great movements intervened between times of relative quiescence, a feature that ran through all subsequent history. Even in this early age, there are signs of glaciation in mid-latitudes and apparently at moderate elevations (Coleman), a feature of vital significance in the interpretation of the climatic history of the earth.

Following another great interval, marked by unconformity, the

Paleozoic Era was ushered in, and with it the first good record of the specific forms of life. The feature of supreme interest, the first good record of life, falls to the lot of my successor, who will give its interpretation and sketch the subsequent life evolution. During the Paleozoic Era there was a series of relatively quiescent periods during which the joint forces of the atmosphere and the hydrosphere made great progress in cutting away the protuberances of the continents and depositing the débris in great sub-sea terraces about the continental borders and in the infra-continental basins, thus partially base-leveling the land, and partially filling the basins, so that the ocean waters crept forth on the borders of the land and seemed to threaten complete submergence. But rarely was more than half the continent conquered before internal stresses had accumulated in sufficient force to bring on another epoch of deformation and continental protrusion, pushing up the land and pushing back the sea, restoring in a measure the old status and preparing the way for a new sea-transgression. After some half dozen periods of such oscillation, a more marked series of deformative movements ensued, with a more pronounced rejuvenation of the land. With this came also the most remarkable of all known glaciations. Mantles of ice gathered on lands near the circles of Cancer and Capricorn and left distinctive records which, however seemingly incredible, are incontestible. To add to the seeming strangeness, the evidence clearly points to low altitudes of the land and to the descent of the land-ice into the waters of the sea which bore icebergs to long distances and formed extensive glacio-natent deposits. That the great deformative action had some genetic relation to this remarkable climatic episode, seems eminently probable, but it does not seem to have accomplished this directly by the elevation of the sites of glaciation.

These remarkable events ushered in the Middle Ages of geology—as much a misnomer as the Middle Ages of human history—the early stages of which seem to have witnessed the greatest extension of land, and apparently the greatest general aridity of climate, known to geological history. But, in time, the persistent gnawings of the atmosphere and the hydrosphere—geologic twins in never-ceasing activity—cut down the great embossments and permitted the sea to transgress the land repeatedly before the Mesozoic Era closed. But, as ever before, the land persisted and was periodically renewed. After fewer oscillations than in the Paleozoic Era, another notable epoch of diastrophism intervened, and the Cenozoic Era was inaugurated. Glaciation seems to have recurred in mid-latitudes (Atwood), but the evidence is as yet less ample than in the preceding transition.

After a shorter succession of base-levelings and sea advances, separated by minor rejuvenations of the land, there came the recent great series of deformations which gave rise to the present great folded mountains, the present great plateaus, and the special configurations which the continents and oceans now bear, save in relatively trivial details. Close on the heels of this great diastrophic epoch came on the last great glaciation in mid-latitudes. At that time, ice-sheets crept down on the American plains to the Ohio and Missouri rivers, and over the northern plains of Europe, while in the southern hemisphere and on mountain heights, even in the tropics, there were signs of a general depression of temperature. There were repeated advances of the ice-sheets, separated by milder intervals during which retreats took place, showing, even in such episodes, the tenacity of the principle of oscillation in terrestrial ongoings. It is only recently, geologically speaking, that the ice-sheets have retreated from the lands where half the civilized world now lives. Glaciers linger in the polar fields and on the mountain heights. The deep sea is still icy cold. The contrasts of climate are sharp. We seem to be yet in the cold segment of the climatic cycle. Whether we are about to emerge into a period of typical mildness, or are yet to suffer a recurrence of the ice invasions, is a geologic detail beyond safe prophecy, but that such emergence is to follow, sooner or later, seems assured by the long history of oscillations of the past and the persistence of recovery that seems to be firmly based on the automatic regulation of the atmosphere and of climate inbred in the very constitution of the earth.